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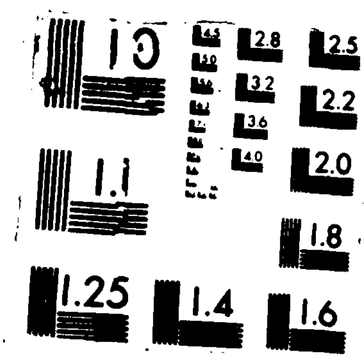
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Sensor and Guidance Technology Related to Mobile Robots

by
S.C-Y. Lu
T.P. Brand
S.G. Kapoor

In case of a national mobilization, the Army needs a technique to construct training facilities rapidly without using a large pool of skilled labor. This can be achieved by borrowing robot technology used to increase productivity in manufacturing. However, most construction activities require mobility. This report contains a list of requirements for mobile robot sensor and guidance systems for mobilization construction. An evaluation of the current state of the art in mobile robot sensor and guidance systems is included. The report then looks at the feasibility of integrating current components to form a practical sensor and guidance system for mobile construction robots. Finally, the report makes recommendations for basic research needed in this area.

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In case of a national mobilization, the Army needs a technique to construct training facilities rapidly without using a large pool of skilled labor. This can be achieved by borrowing robot technology used to increase productivity in manufacturing. However, most construction activities require mobility. This report contains a list of requirements for mobile robot sensor and guidance systems for mobilization construction. An evaluation of the current state of the art in mobile robot sensor and guidance systems is included. The report then looks at the feasibility of integrating current components to form a practical sensor and guidance system for mobile construction robots. Finally, the report makes recommendations for basic research needed in this area.

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FOREWORD

This research was conducted as an In-Laboratory Independent Research Project, under 41A61101A91D-04, Work Unit 117, "Robotics in Construction." The authors were contracted for this work from Department of Mechanical and Industrial Engineering, University of Illinois, Urbana-Champaign. The Facility Systems (FS) Division, U.S. Army Construction Engineering Research Laboratory (USA-CERL), monitored the work. Mr. Robert B. Blackmon was USA-CERL's principal investigator. Mr. Edward A. Lotz is Chief of FS.

COL Norman C. Hintz is Commander and Director of USA-CERL. Dr. L.R. Shaffer is Technical Director.

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CONTENTS

SENSOR AND GUIDANCE TECHNOLOGY RELATED TO MOBILE ROBOTS

1 INTRODUCTION

Background

During a national mobilization, the Army needs to construct large training camps rapidly using very little skilled labor. In addition, facility construction must be accelerated while maintaining an adequate level of quality. These needs can be achieved by applying some of the same techniques that increase productivity in manufacturing. Manufacturing systems use robot technology to reduce production cost, provide line flexibility, improve product quality, and improve the management of the total manufacturing process. However, robot-based manufacturing technology cannot be applied directly to building construction because of the great difference in required tasks and working environment.

In the manufacturing environment, the robot operates in a fixed position in the assembly line. The product moves around the robot and the relative position of the robot's end effector and the parts to be manipulated are always known, either by precise fixturing or sensor systems. The construction environment, however, is unstructured and always changing. Almost all construction tasks require mobility. This suggests that robotic construction will require mobile robots with sophisticated sensor and guidance systems.

Up to now, a great effort has been made to develop practical sensor and guidance systems for controlling robot manipulator movements, but the more difficult task of controlling a mobile robot has received much less attention. A significant amount of research in this area is needed in order to apply robotic techniques to construction. The two critical areas for this research are sensor and guidance systems for mobile robots.

Objective

The purpose of this research is to assess the current state of the art in mobile robot sensor and guidance technology in order to identify technology shortfalls and make recommendations for needed research in this area.

Approach

This assessment was based on current books, papers, conference proceedings, and trade periodicals in the field of mobile robot sensor and guidance technology. Chapter 2 defines the problem and describes construction in general and mobilization construction in detail. It also describes what others have done regarding the use of robots in construction. A list of requirements for mobile construction robots' sensor and guidance systems is included. Chapter 3 assesses current mobile robot sensor and guidance technology. It describes how some researchers are approaching the problem of guiding mobile robots and the ongoing research in this area. Chapter 4 compares what is required for mobile construction robots' sensor and guidance systems to what is available. It discusses the feasibility of integrating available components to form a practical mobile robot sensor and guidance system and it identifies technology shortfalls. Chapter 5 identifies basic research needs in sensor and guidance technology for mobile construction robots.

2 THE APPLICATION OF ROBOTICS TO CONSTRUCTION

Introduction

Before making recommendations for using robots to perform construction tasks, one has to understand the types of tasks which construction requires. Robotic construction differs from robotic manufacturing in several ways. Most notable among the differences is the working environment. Construction is performed in a highly unstructured environment as compared to the very structured manufacturing environment. Since construction robots have to move around the products (e.g., buildings and warehouses), their environment is continually changing. This is different from production applications in which the products always move around the robots. Although individual construction tasks are well defined, the interactions between robots and construction tasks are not. The tasks will influence the design of construction robots, and the robots will lead to the modification of the tasks.

Construction in General

Construction activities are generally performed in a very unstructured and dynamic environment. The construction environment is characterized by varying terrain, unpredictable weather, and numerous obstacles. Unlike most manufacturing activities, construction is a very mobile activity requiring highly skilled workers who must perform in sometimes harsh or hazardous conditions. Construction activities consist of preparing the site, handling building components, connecting components to existing structures, and finishing them by application of appropriate mechanical treatments. Sangrey and Warszawski[1]* have listed all of the basic building construction activities (Table 1). Most building components are much larger and heavier than assembly components used in manufacturing. However, some of the robotic techniques used to increase productivity in manufacturing can be used to increase productivity in construction. By analyzing the basic construction activities it was concluded that four types of construction robots can perform most building construction activities:[1,2] the Assembly Robot, General Purpose Robot, Exterior Wall Robot, and Floor Finishing Robot (Figure 1).

The Assembly Robot would handle and position large building components and might be configured like a building crane. This type of robot must be able to handle heavy objects. It may require, depending on the building component, human assistance in attaching or temporarily bracing a large component to the building structure. The General Purpose Robot would be used for interior connecting and finishing work. It would be much smaller than the Assembly Robot, and would be equipped with the appropriate tool for performing a specific task. The Exterior Wall Robot would consist of a vertical carriage suspended from the roof of a building. This type of robot is intended for finishing and inspection activities. And finally, the Floor Finishing Robot is intended for horizontal finishing operations, including paint or glue spraying. This robot would consist of an end effector mounted underneath a self-propelled carriage. All of these robots require a sensor system and an intelligent way to interpret the information provided by the sensors.

Sensor systems for construction robots will be needed for many different tasks, including collision avoidance for both the robot's arm and body. The robot must be able

*Numbers refer to reference list beginning on page 41.

Table 1. Basic Activities in Building Construction

No	Activity	Description	Examples
1	Positioning	Placing a large object at a given location and orientation	Erection of steel beams, precast elements, formwork, scaffolding
2	Connecting	Connecting a component to an existing structure	Bolting, nailing, welding, taping
3	Attaching	Positioning and attaching a small object to an existing structure	Attaching hangers, inserts, partition boards, siding, sheathing
4	Finishing	Applying continuous mechanical treatment to a given surface	Trowelling, grinding, brushing, smoothing
5	Coating	Discharging a liquid or semiliquid substance on a given surface	Painting, plastering, spreading mortar or glue
6	Concreting	Casting of concrete into molds	Casting of columns, walls, beams, slabs
7	Building	Placing blocks next to or on top of others with a desired pattern	Blocks, bricks or stones masonry
8	Inlaying	Placing small flat pieces one next to the other to attain a continuous surface	Tiling, wood plank flooring
9	Covering	Unrolling sheets of material over a given surface	Vinyl or carpet flooring, roof insulation, wall fabric
10	Jointing	Sealing joints between vertical elements	Jointing between precast elements and between partition boards

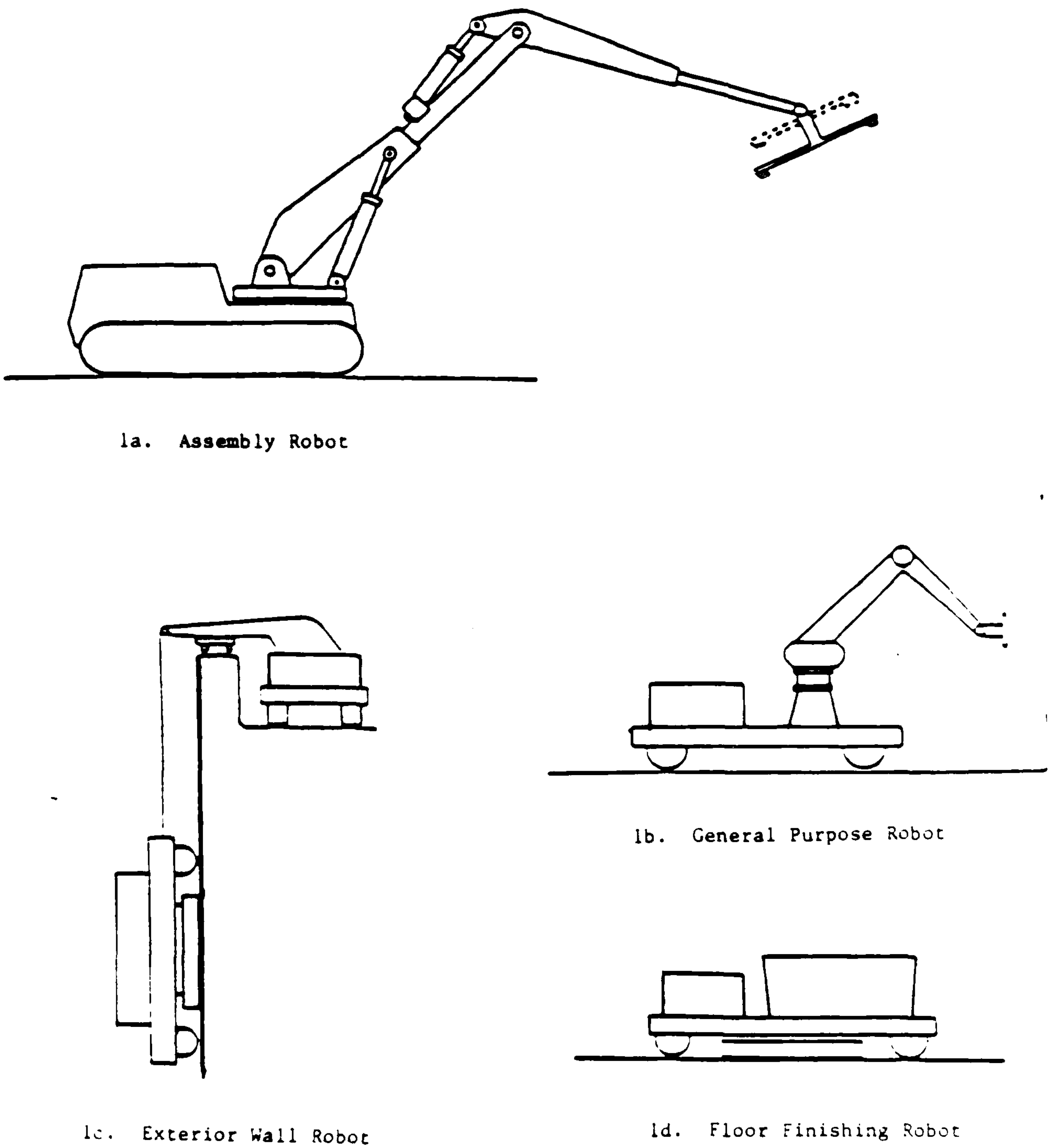

Figure 1. Construction robots.

to verify a preprogrammed work path; for example, welding a seam or any type of jointing activity. Another important task would be quality inspection. The most important use of sensors for a construction robot would be for a navigation or guidance system. The robot must be able to plan paths for its body as well as its arm and end effector. Practical navigation systems for mobile robots represent one of the most challenging areas of robot research.

To date, robot use in construction for other than research has been almost nonexistent. A list of current commercial applications of robotics in construction is given by Sangrey and Warszawski.[1] These applications include shotcreting, tunneling, concrete pouring, rock drilling, spraying fire-proofing material, tree harvesting, and a few others. Automation techniques are being used in factories which build prefabricated housing components.[3]

Mobilization Construction

Mobilization construction has two outstanding characteristics which separate it from normal commercial construction. First of all, during national mobilization, Army training facilities must be constructed very quickly and with the same quality found in peacetime construction. Second, this speed and high quality must be achieved with an extreme shortage of skilled manpower. To meet these requirements, the Army is looking at the possibility of developing a mobilization plan which uses modular construction designs.[4] This approach uses repetitive building dimensions and components to simplify construction. This would make the on-site fabrication of trusses and panels feasible. All the materials required to construct an Army training facility could be stored at a warehouse near the construction site.[5] Developing a means to deliver materials to the construction site as needed would increase the efficiency of the entire construction process. Constructing a typical building will entail several operations which can be grouped into the six categories discussed below.

Site Work

Mobilization facilities will ideally be built on relatively flat, unobstructed terrain to save time on site preparation. The typical barracks will be built using either pier or slab-on-grade construction. In pier construction, the ground can remain relatively untouched, because the building is elevated some distance off the ground. In slab-on-grade construction, the building rests on a concrete slab which requires level ground. The site is leveled using basic earthmoving operations.

Foundation Work

In pier construction, the piers must be set vertically (with the tops level) using either optical or more sophisticated laser techniques. In slab-on-grade construction, forms must be built and gravel spread over the foundation site. Buried plumbing and electrical items must be installed before the concrete is placed and finished. When the concrete has set, the forms are removed and backfilling operations performed.

Wood Framing

Roof trusses, floor trusses, wall panels, roof panels, and floor panels could be fabricated on site. Most of the fabrication work could be completed as described by Gatton.[4] This plan includes using a portable robotic factory to construct trusses. Once the fabrication is completed, wall panels, complete with window and door frames, are attached to the floor. The roof trusses are then positioned on top of the walls. Roof trusses are usually positioned with a crane and work crew. In almost all of these processes, temporary bracing is required.

Sheathing and Flooring

Usually the plywood flooring is attached to the floor joists before the walls are erected. Plywood sheathing is placed on the outside of wall panels and roof trusses. This process involves positioning sheets of plywood and nailing them into place. If the wall panels are fabricated on site, the plywood sheeting is installed before the walls are erected.

Mechanical, Electrical, and Plumbing Systems

Mechanical, electrical, and plumbing work is performed during all stages of construction and must be completed in the building shell before the interior finish is applied.

Finish Work

Finish work involves insulating, drywalling, painting, and installing floor coverings, roofing, and any type of final covering. If it were possible to make all structural connections from the interior of the building, the exterior weather surface could be installed during the fabrication process.

Mobilization construction needs to use the best construction techniques available. Buildings could be designed to take advantage of modular construction. This would allow fast construction and the ability to expand buildings by adding on basic units. Modular construction would allow the mobilization construction environment to be slightly more structured than a commercial construction environment. Using a central warehouse would make the task of delivering building materia'_ to the construction site more efficient. Another way to make the construction proce.s more efficient would be to use robotic techniques to increase productivity.

Sensor and Guidance System Requirements for Mobilization Construction

In mobilization construction, two of the four types of construction robots described earlier are required: the Assembly Robot and the General Purpose Robot. The Assembly Robot would place floor trusses, roof trusses, wall panels, floor panels, and roof panels on the foundation. The General Purpose Robot would do the interior connecting and finishing work, such as insulating, drywalling, and painting. An Exterior Wall Robot would not be needed because it would be more efficient to finish the plywood before erection. The Floor Finishing Robot would not be needed because tile floors are used in the barracks. There are, however, some tasks that do not exactly fit into any of the types of tasks performed by the four types of construction robots.

One type of robot would have the special task of transporting material from the warehouse to the construction site. This Material Handling Robot would not participate in assembly activities, but would instead deposit lumber and material in predefined locations for Assembly Robots to pick up as needed. Another type of robot would perform tasks which are required before the concrete slab is poured. This Site Preparation Robot would install buried utility systems. For mobilization construction, the utility systems would include electrical, water, sewer, and communication lines. For the more general construction case, gas and steam lines would be included as well.

It is apparent that the problem of controlling a mobile construction robot is one of guiding the robot's body and controlling the robot's end effector. This requires sensors for both navigation and operation. Two types of guidance systems are required for mobilization construction: an indoor and an outdoor guidance system.

Indoor Guidance System Requirements

Type of construction robot: General Purpose

Type of environment: This guidance system would have to operate inside facilities under construction. The surroundings would consist of a series of rooms with wood frame walls and flat plywood floors. Depending on the stage of construction, the robot would be exposed to all types of weather.

Sensor requirements: The sensors must be able to detect obstacles and provide range data for objects up to 12 m(meters)* away.

Navigation requirements: Since the robot would require knowledge of the layout of the building, its navigation system would consist of locating itself on an internal map and planning appropriate actions. It must also have obstacle avoidance algorithms.

Outdoor Guidance System Requirements

Type of construction robot: Assembly, Material Handling, and Site Preparation.

Type of environment: These robots must operate all over the entire undeveloped construction site. The terrain would be rough with no surface drainage control. The robots would be exposed to all types of weather. Depending on the weather, they would be exposed to dust or mud.

Sensor requirements: Long and short ranging sensors are needed. The sensors must also be able to detect obstacles (including open ditches and other excavations), workers, and other mobile robots.

Navigation requirements: The robot would initially require limited knowledge of the construction site. The navigation system must allow the robot to move around the exterior of the building and locate predefined points both on and around the building. It must also allow the robot to find building material stacked around the building. In the case of the Materials Handling Robot, the navigation system must guide the robot from the warehouse to predefined locations around the building site for accurate placement of building components. The Site Preparation Robot must be able to excavate ditches and install utility systems with respect to a reference point.

Sensor Requirements

The type of sensors and controllers required to operate the robot's end effector is task specific. Ideally, all robots intended for either indoor or outdoor construction activities would have the same generic guidance system. The end effector, control

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*Conversion factors are on page 40.

system, and operating sensors would determine which construction activity the robot performs. There are several tasks required of sensors and controllers for each of the construction operations described earlier in this chapter.

Quality Control. This includes determining the physical condition of the building material before installation (moisture content, deformed sections, or damaged sections), and the quality of the work after the task is performed.

Controlling a Process. This includes controlling the path of the end effector. The end effector must be guided over a prescribed area for such activities as nailing or caulking. The robot must also monitor the supply of fasteners or coating which it is applying.

Manipulating Components. This includes picking and placing building components. For example, the robot must know the position and orientation of a sheet of plywood when attaching it to a wall frame. It must also be able to tell if the proper side of the plywood is facing the exterior.

3 CURRENT TECHNOLOGY

Sensor Technology

As discussed in Chapter 2, mobile construction robots require sensors for both guidance systems for navigation and control systems for performing construction operations. With the exception of contact switches and wheel encoders, navigation systems use noncontact sensors (i.e., visual or ultrasonic). Vision systems are also very important for controlling robot manipulators and for quality inspection. Control systems require both contact (tactile) and noncontact sensors. For example, tactile sensing is very important for controlling robot grippers. The sensors discussed below are available for mobile robot guidance systems; however, a section on tactile sensors is included for completeness.

Vision Systems

Just as machine vision systems are an important part of industrial robot sensor systems, they are also an essential component of many mobile robot guidance systems. The two primary elements of a machine vision system are a camera and a computer video image analyzer. The camera images a scene, which is then analyzed for the desired information. The features usually extracted from the scene are pixels (picture elements), texture, regions, edges and lines, and corners.[6] The two types of cameras used are the video-tube vidicon and the solid-state camera.[7]

Television cameras using vidicons are used by vision systems to obtain analog electrical signals. The vidicon has several disadvantages, primarily because it is used in a TV camera, which is designed to provide pictures for entertainment and not industrial vision tasks. These disadvantages include nonuniform response (the best gain and resolution are at the center of the picture), poor linearity, electron beam deflection by external forces, and the lag of camera tubes. Also, video-tube cameras are fragile. However, a new image manipulating camera, ROTOZOOM, uses a vidicon and has been designed specifically for industrial vision tasks.[8] It begins to solve some of the problems caused by using a TV camera designed for eye viewing. One characteristic of this camera is that it can zoom in on a feature without losing any resolution, unlike a windowed section. The ROTOZOOM maintains a resolution of about 500 lines. A windowed section only has a resolution of about 50 lines. Another feature of the ROTOZOOM is that it can automatically rotate an image.

Solid-state cameras consist of arrays of silicon detectors called charge-coupled devices (CCDs) which generate an electronic signal that is proportional to the incident of light. CCD's pixel array sizes used in vision systems range from 32 by 32 to 320 by 512 pixels.[7] Linear arrays are commercially available in sizes ranging from 16 to 2048 pixels.[2] The processing time for matrix cameras is directly proportional to the array size (1/4 second for a 128 by 128 array, 1/16 second for a 64 by 64 array, etc.).[7]

Vision systems are used by industrial robot assembly systems for such functions as determining object orientation, recognizing parts, and inspecting the product. They are also being used to follow seams during robotic welding. In mobile robot guidance systems, they have been used for ranging,[9] roadway following,[10] and local positioning.[11] Due to the vast amount of information that has to be processed with vision systems, it follows that mobile robots using such systems are very slow. Access to a large computer would increase the robot's speed. Generally, it takes 250,000 KBytes to store a preprocessed vision image.[12] Because of this, most mobile robot research uses ultrasonic or sonar range sensors.

Ultrasonic Transducers

Ultrasonic ranging or sonar is accomplished by using a capacitive transducer made of a very thin metalized diaphragm supported over a specially machined backplate. The transducer emits a short burst of constant frequency signal and then switches to the receiver mode to wait for the echo return.[13,14] Ultrasonic ranging systems have several sources of error associated with them; the speed of sound is temperature dependent, certain surface characteristics can cancel a single-frequency waveform, and a wide beam may cause incorrect readings. A large beam width can cause a narrow vertical object, such as a wooden dowel, to appear much wider than it actually is. A doorway may not be perceived at all if the beam width is wider than the opening. Another source of error occurs when the angle of incidence of the beam decreases below a critical angle. When this happens, the beam can be reflected away from the transducer, which causes the transducer to totally miss the object. Also, the beam echo can be reflected around the room and back to the transducer, which causes the calculated distance to the object to be much greater than it actually is. The angular resolution of ultrasonic ranging systems can be increased by using multielement ranging arrays.[15] One very popular device is the Polaroid electrostatic ultrasonic transducer which has an effective range of 0.3 to 10.6 m and emits a "chirp" of four discrete frequencies. This solves the problem of a single-frequency waveform being canceled by a surface. Ultrasonic sensors are extremely well suited to detecting objects such as large flat walls, and to proximity sensing for obstacle avoidance.

Wheel Encoders

A relatively simple and inexpensive way to estimate the position of mobile robots is by using wheel encoders. Wheel encoders count shaft rotations. Position is estimated through trajectory integration. Different types of encoders are described by DeSilva.[16] Both incremental and absolute encoders are available and there are many different types available, including optical, resistive sliding contact, magnetic saturation, and proximity probe. Wheel encoders provide information with almost no time delay, but small errors due to wheel slippage can grow very quickly in an unbounded manner.[17] Some wheel slippage can be detected and compensated for by comparing the instantaneous angular velocity to the running average velocity.[11]

Contact Switches

Contact tactile switches placed around the base of a mobile robot are used as proximity sensors primarily for collision avoidance.[11,16,17] Contact switches provide binary information--either the robot is in contact with an object or it is not in contact with an object.

Magnetic Proximity Sensors

Magnetic proximity sensors are often used as metal detectors. A magnetic proximity sensor consists of a coil driven by an oscillator. This induces an oscillatory magnetic field in the coil. When a conductor is brought within the range of the coil, induced eddy currents increase the frequency of the oscillator. This change in frequency is a measure of the distance to the conducting object.[14] Magnetic proximity sensors are being used in wire-guided vehicles.[18]

Infrared Sensors

Infrared sensors can be used as proximity sensors, motion detectors, and goal-seeking sensors.[9,19] The home entertainment mobile robot Brains on Board, or BOB, uses an infrared sensor tuned to the wavelength of the human body to locate people in a room.[11]

Laser Range Finders

Another type of sensor used in mobile robot research is the laser range finder. A LIDAR (Light Detection and Ranging) system usually measures the time of flight of a pulse of light. It is used in many civil engineering and military applications for measuring large distances; however, it is very expensive. Because the speed of light is so great, even the most expensive systems cannot measure distances of 0.305 m or less. Laser-based phase measurement devices are available that operate over the range of 0.5 m to 8 km (kilometers), but they require expensive retroreflecting targets.[13]

Level Sensors

Pitch and roll sensors mounted on gimbal rotation axes provide level information. This provides a mobile robot with a measure of the steepness of grade it is traveling over.[11]

Goal-Seeking Sensors

Goal-seeking sensors are grouped together because of their use, not because of their operating characteristics. Sensors exist that can sense infrared emitters or a speaker emitting a certain frequency. One inexpensive and easily constructed goal-seeking sensor uses a modulated light source.[20] These types of sensors can be used by a mobile robot equipped with obstacle avoidance routines to maneuver to a desired location in its environment.

Global Positioning Systems

Global positioning systems are used to find the position of an object by determining distances to fixed beacons. Sensors used in goal-seeking sensor systems can be used for this purpose. Global positioning systems exist that use cameras to image fixed location markers.[11] The LORAN (Long Range Navigation) system is a hyperbolic navigation system used by ships. It uses radio frequency beacons and receivers to determine the time delay for a radio signal to travel from known location beacons to permit triangulation of position.[11] The accuracy of a LORAN system is on the order of tens of feet. A local LORAN type system could be built; however, it would require active transmitters as well as receivers. NAVSTAR is a satellite-based global positioning system. Systems like LORAN and NAVSTAR are very expensive.

Tactile Sensors

Tactile sensors can be used to detect an object's presence or to indicate the value of the force being exerted on the sensor. A contact switch can be used to indicate an object's presence. When using a contact switch in conjunction with a spring-loaded fixture, the switch will be tripped when a known force is applied. Tactile sensors like this can be configured in an array. An 8 by 8 array of tactile sensors has been used by researchers for object recognition.[21] These tactile sensors consist of an elastomeric pad at each sensing site. Beneath each sensing site is a plunger which modulates the intensity of a Light Emitting Diode (LED) such that the output of a photodiode is proportional to the plunger's deflection. Using a potentiometer or a Linear Variable Displacement Transformer (LVDT) and spring can give a measure of an applied force which is proportional to the deflection of the spring. Most work to decrease the size and increase the density of proportional sensor arrays still remains in research laboratories.[22] Strain gages are also used to measure the force applied to a member and the deflection of a member. Magnetoelastic ribbons have been used as force feedback sensors in a robotic wrist.[23] They are supposed to have greater sensitivity and simpler transducer signal processing electronics than strain gages. Optical fibers are being used in grasping systems to detect contact with an object.[24] Research is being conducted on an induced vibration touch sensor.[25] This sensor uses an artificial "skin," a polyvinylidene flouride sensing element, which is dragged across an object. By measuring the induced vibrations in the "skin," it is possible to recognize objects.

Guidance Technology

Intelligent Mobile Platform (IMP)

This project is being conducted by the Laboratory for Household Robotics at Carnegie-Mellon University (CMU).[17,26] The prototype of the IMP contains a rotating depth sensor mounted on the top (Figure 2). The sensor rotates one revolution every 5 seconds and detects the distance to the nearest surface within 6.1 m with a resolution of 0.03 m. The IMP has two free-rotating passive wheels and two stepper motor-powered wheels. The stepper motors simulate incremental wheel encoders by counting the pulses sent to the motors. The IMP contains hardware to perform speech synthesis and speaker-dependent isolated-word speech recognition. It also contains two 16-bit micro-processors. The guidance system for the IMP is based on a computational paradigm which is a framework of data structures and processes which perform some task.

The guidance or navigation system is based on maintaining a dynamic internal model of the robot's local environment. The navigation system creates a "composite local model" and "sensor models." The sensor models provide information which is integrated into the composite local model. The composite local model is a dynamic model of the surfaces and objects in the immediate surroundings of the robot. The known universe of the IMP is represented by two related data structures: the "global model" and the "network of places." These two data structures are "taught" to the IMP in a learn mode. The global model is made up of all the composite local models obtained as the robot is taught its surroundings. The places are convex regions or locations named by the user during training. The pathways between places are represented by a "doorway region" and a pair of "adits." The IMP navigates by determining the shortest path through the adits from its starting point to its goal. The IMP moves in straight line paths through the places from adit to adit until the final goal is reached. The navigation system also does local path planning if an obstacle is detected in its path when moving through a place. The IMP estimates its position instantly by using its wheel encoders. This estimate is corrected by comparing it to the information obtained from the rotating depth sensor. The guidance system for the IMP is being refined using an interactive mobile robot simulation program.

The simulation program provides the user with three windows. A dialogue window is used for text debugging messages and commands. A sensor and composite local model window shows the robot's view of the world using simulated sonar and contact sensors. The largest window shows the actual floor plan and the robot's actions as it guides itself

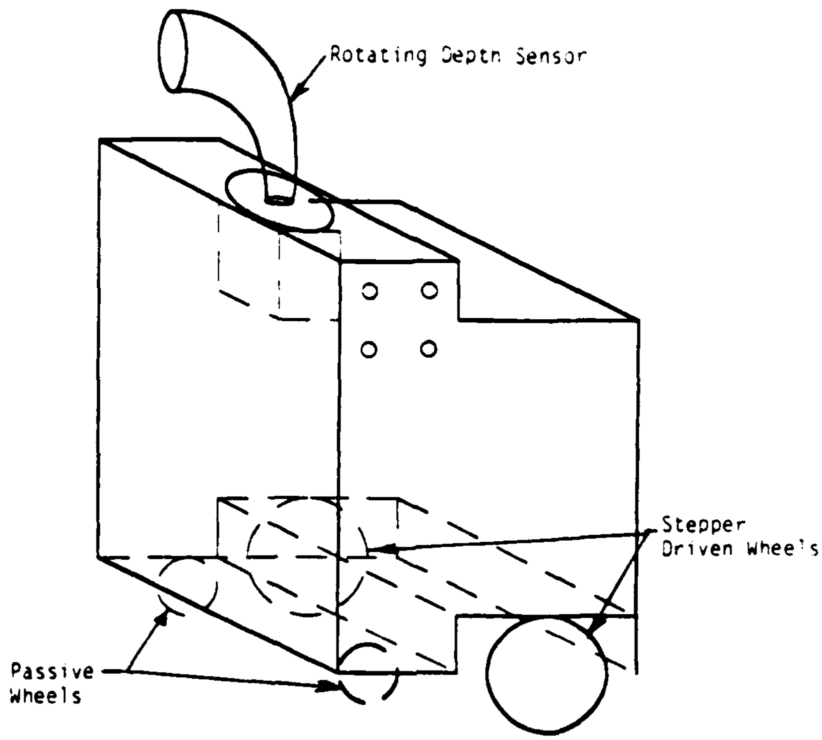

Figure 2. The Functional Components of the IMP.

through its world. Simulating the guidance system allows the researchers to develop IMPs using other types of sensors and world modeling techniques.

Stanford Cart and Rover/Pluto[3,27]

The Stanford Cart was a four-wheeled cart that steered like a car. Its sensor system consisted of a camera mounted on a sliding track. The Cart took nine stereo images with the sliding camera in order to use stereopsis to locate objects in its own domain. An "interest operator" selected interesting features in one scene and then used a "correlator" to locate the same objects in other scenes. The obstacles were modeled as circles on a two-dimensional map of the courses. The Cart's path planning consisted of determining the shortest path along tangent segments between the circles. The Cart moved in 1 m lurches every 10 to 15 minutes. Not only was the Cart exceedingly slow, but it did not see all objects reliably. Its movement was not very repeatable due to the wheel configuration. The Cart was tested on indoor and outdoor obstacle courses. Reflected sunlight caused problems during outside runs. The Cart led to the development of the Carnegie-Mellon University (CMU) Rover.

The CMU Rover was designed with three individually steered wheel assemblies which were intended to give three degrees of freedom in the steering plane. The sensor system includes a TV camera mounted on a pan/tilt/slide mount, Polaroid ultrasonic transducers, short-range modulated infrared proximity sensors, wheel encoders, and contact switches. A combination of a VAX 11/780 host computer and an ST-100 array processor provide processing power at the other end of a remote-control link. The Rover has a dozen onboard processors. The Rover was intended to continue the work done with the Stanford Cart on visual navigation.

Path Relaxation[28] is part of FIDO, the vision and navigation system of the Rover. Path relaxation is detailed later in this chapter. The robot picks 40 points to track with the vision system. FIDO's world model is not suitable for most path planning algorithms, because it does not assume a completely known world with planar-faced objects. Its world model consists only of the 40 points it is tracking.

The CMU Rover was completed in 1983. When testing started, several severe design flaws related to its omnidirectional wheel design were uncovered; the wheel assembly shaft encoders malfunctioned and the glass encoder disks broke, the differential wheels lost traction on slight floor irregularities, the motor driven field-effect transistors burned out, and the drive and steering motors experienced severe oscillations. The Rover has been renamed Pluto and the problems associated with its omnidirectional drive system are being corrected. Until these problems are solved, Pluto will be unsuitable for visual navigation work. An omnidirectional wheel design that is controllable has been developed by Unimation Inc., in cooperation with the Department of Mechanical Engineering, Stanford University.[29]

Neptune

Neptune is a mobile robot developed at the Mobile Robot Laboratory of the Robotics Institute at CMU.[10,30] It is a tricycle with a powered and steered front wheel and two passive rear wheels. It contains a ring of 24 Polaroid ultrasonic transducers and a two-camera stereo vision system. A VAX 11/780, with a Grinnell digitizer tethered to the vehicle, performs vision and navigation functions. An onboard 68000 microprocessor is used for motor control and camera switching. It is used in a variety of mobile robot research.

The sonar sensors are used to create a high resolution map of the robot's environment. The map is made up of regions that are classified as empty, occupied, or unknown. Researchers developed a way of convolving two sonar maps made from two different locations of the robot. They presently use the path relaxation method[28] to plan local paths for the robot.

The navigation algorithms developed for the Stanford Cart have been implemented on the Neptune using a two-camera vision system instead of one camera mounted on a sliding track.[31] The system still uses the stop-go-stop method of moving along an obstacle course. Researchers have reduced the program run time by reducing the number of images taken at each stop and by increasing the amount of constraints on image correspondence. The performance of the correspondence algorithm was improved by constraining the search to a smaller area of the scene and by picking better features to match. Researchers plan to match larger semantic units such as edges, bounded regions, or objects instead of points.

The Neptune was also used at CMU by the Autonomous Land Vehicle (ALV) group. The Neptune had two cameras (for stereo vision work) mounted on it. The cameras were used to obtain scenes of a roadway (at first black electrical tape on the floor, then outdoor sidewalks). The edges of the roadway in the scene could then be extracted for the navigation system which would keep the robot centered on the roadway. The next step in this roadway following research resulted in the implementation of this system on the Terregator.

Terregator

The Terregator is a six-wheeled outdoor vehicle used in the CMU ALV project.[30] The three right wheels are driven by one motor and the three left wheels by another. Shaft encoders count wheel turns but they are not very accurate because of the skid steering. A VAX 11/780 with a Grinnell digitizer performs most of the computations via a radio link. In addition, the Terregator has a 68000 microprocessor on board. The Terregator has one black and white camera for a vision system.

The guidance system consists of locating roadway edges and then keeping the robot centered between the edges. Researchers used several different methods of line and edge extraction to accomplish the task. Continuing research will include trying other vision methods such as texture and color operators. Further work will include using a magnetic compass, a gyro, and a map. Obstacle avoidance which will require limited three-dimensional processing is also planned.

Hilare

Hilare is a mobile robot designed under the direction of George Geralt in Toulouse, France. Chatila and Laumond[32] developed a guidance system which is partially implemented on Hilare. The robot relies on two types of sensors for path planning: a laser range finder and optical shaft encoders. It uses an ultrasonic system for obstacle avoidance. It is presumed that the robot has a proximity sensing system for docking at work stations. The design approach is based on defining general principles to handle uncertain sensors and a methodology to enable the mobile robot to define its own reference landmarks while it explores its environment. The robot needs three types of world models. It deduces a geometrical model from sensor data. A topological model is made up of places or cells. A semantic model contains information about the properties and relationships of objects and spaces. This system uses three position referencing techniques: (1) the robot uses absolute position referencing based on fixed or known beacons to compute its location at any time, (2) the odometer system is used for trajectory integration without the need for an external reference, and (3) the robot defines its relative position with respect to objects or places. The robot explores its environment and estimates its positions by averaging weighted information from each type of sensor. The weighted information is based on the uncertainty associated with each sensor.

DARPA

The Defense Advanced Research Projects Agency's (DARPA) Strategic Computing Program is developing an ALV as part of a major effort to develop and demonstrate a machine intelligence capability which is applicable to national defense. The Computer Vision Laboratory at the University of Maryland[33,34] is designing and developing a vision system which is supposed to drive the ALV over a network of roads at speeds up to 10 km/hr. The vehicle will be equipped with TV sensors, an active ranging sensor, and a sophisticated inertial guidance system. The ranging sensor is currently being constructed at the Environmental Research Institute of Michigan and will be capable of acquiring two 100 by 100 arrays of range data per second. A group of computers including a VAX 11/750 and a VICOM image processor will drive the vehicle.

The visual navigation of roadways is achieved by three vision modules. These modules establish a representation of the three-dimensional structure of the roadway. The "navigator" plans paths subject to goals and constraints imposed by the "mission planner." The "pilot" executes the path commands. Roadway following is divided into a "boot-strap" phase and a "feed-forward" phase. Boot-strapping implies that the vision system processes roadway images without any prior visual processing. Feed-forward implies that the roadway was previously traveled, which means processing demands could be reduced by using previous knowledge. The image processing system uses a segmentation algorithm to extract dominant linear features from the scene. The first goal of this research was to navigate a single, obstacle-free road with no intersections at speeds up to 5 km/hr. This was demonstrated during late summer 1985.

The system will eventually be able to navigate and locate its position on or off the road. The visual navigation system uses a landmark-based vehicle positioning system. Three modules are used to establish the vehicle's position. The "matcher" uses a Hough transform to locate likely positions for landmarks in an image and then rates them according to confidence measures. The "finder" controls the pointing direction and focal length of the camera and directs the matcher to find landmark positions. The "selector" identifies landmarks whose recognition would improve the position estimate of the vehicle. It directs the finder to find these landmarks and then calculates an estimate of the vehicle's position from the estimated position of the landmarks. The vehicle does path planning by using a "quadtree" multiresolution representation of its surroundings and an A* search[35] to find the best path.

Hermies-I

Hermies-I (Hostile Environment Robotic Machine Intelligence Experiment-Series I) is a mobile robot developed by the Center for Engineering Systems Advanced Research (CESAR).[36] Hermies-I contains a dual set of independent direct current (dc) motor-driven wheels with a common axle alignment, dual manipulator arms, onboard processors, and a pedestal-like sensory platform. The platform contains two ultrasonic ranging sensors and a solid state camera. Actual experimentation with the Hermies-I has been limited by its crude sensor and end effector capacities. Researchers intend to try tasks that involve vision and one or two of the manipulator arms. Navigation algorithms are being tested by graphic simulation. Researchers use a Lisp Machines Incorporated (LMI) LISP machine which produces real-time graphics. It shows obstacles and relative movement of Hermies-I. They are using a hypercube computer architecture approach to ensure that the several different asynchronously controlled hardware devices such as manipulators, ultrasonic ranging devices, and navigation controller are being used efficiently.

Dynamic Scene Analysis

Tsuji, Yagi, and Asada[37] from Osaka University in Japan are conducting research on guiding a continually moving mobile robot in a manmade environment. The hardware consists of a Heathkit HERO Robot equipped with a CCD camera. A 6808 microprocessor, augmented by an image processor and a 68000 microprocessor, plus four LSI (large-scale integrated) image-processing chips (Hitachi ISP's) convert the input image into a 256 by 256 8-bit digital picture and compute the correlation of the image with a 4 by 4 mask at the video rate. An LMI Lambda machine is used for world modeling and path planning. For dynamic scene analysis, the robot moves at a speed of 0.3 m/sec and takes an image every second.

The researchers use the theory of optical flow and take advantage of the fact that manmade environments have many visible vertical edges and floors that are almost flat. The system estimates the rotational component of camera motion from image points which do not change with translation. After compensating for rotational movements, the system determines the foci of expansion of translational motion of both the robot and moving objects. The motion parameters obtained by this system are not very precise, but give enough information for moving in buildings.

PEGASUS

The PEGASUS system is an example of mobile robot research being conducted at the University of Tennessee.[11] The goal of this project is to develop a sensor and guidance system for the autonomous operation of a commercial lawnmower. To provide autonomous control, the lawnmower is equipped with several sensor systems.

The lawnmower is completely encircled by contact switches which are 15.24 cm from the mower and 15.24 cm above the ground. They provide a last line of defense for obstacle avoidance. Wheel encoders fixed to the mower's hydrostatic drive motors are used to estimate the robot's position. The design includes 12 sonar transducers controlled by 8 stepper motors. Four of the stepper motors are located at the four corners of the mower and each controls two transducers. The other four stepper motors, each controlling one transducer, are located at the front, sides, and back of the mower. The sonar transducers detect objects up to 6.1 m from the robot. A 256-element line scan camera views the front pathway of the mower, detects the grass cut/uncut boundary, and provides corresponding guidance signals. The mower contains a gimbol-mounted fish eye lens camera, which determines position by imaging two or more fixed location markers. The camera has a shutter speed of 250 to 1000 frames per second so that the location markers can be imaged without motion blurring. The sensor system also contains level sensors to detect when the grade is steeper than the drive grade of the mower. The PEGASUS system uses a hierarchical computer control architecture to control the sensor and guidance system. It consists of a 16-bit 8088/8087, MPX-16, single board computer used as the supervisor. This computer is programmed in the FORTH language. The 8087 math coprocessor increases the speed of numerical calculation. Seven Z-8 microprocessors perform as dedicated controllers for individual subsystems.

The PEGASUS will operate in both a training and an automatic mode. In the training mode, the operator will drive the robot around the perimeter of the field and indicate any critical obstacles. During the automatic mode, the PEGASUS uses both a local and a global positioning system. Local positioning is achieved by using the line scan camera and the wheel encoders. Global positioning is achieved by determining the view angles of the fixed location markers in the horizontal and vertical directions. The computer control system can follow one of several different mowing strategies: mowing in strips or around the perimeter, or dividing the yard into sectors and mowing each sector in strips or around the perimeter. For safety, a radio control unit can be used to stop or remotely drive the robot.

The researchers suggest research is needed to develop a satellite-based LORAN system accurate to within a few inches instead of the current accuracy on the order of tens of feet. They also suggest that special very large-scale integrated (VLSI) imaging sensors be developed for omnidirectional global positioning.

Mobile Robot with Artificial Intelligence

Interrante and Biegel[33] are doing research on combining artificial intelligence and robotics. Two types of intelligences, Alpha and Beta, were simulated for a mobile robot on a computer. Alpha intelligence means that the robot has only a fixed set of responses to sensed changes in its environment. Beta intelligence is the same as Alpha intelligence at first. However, a Beta robot remembers the outcome of past responses and uses those experiences to make successful decisions in the future. Alpha and Beta intelligence was implemented on a mobile robot which was required to avoid an obstacle when moving between two workstations. The Beta robot was superior.

The biggest problem confronting the researchers was the inaccuracies of the sensors. Three types of sensors were used: an ultrasonic sensor used as a proximity sensor, eight tactile sensors or bumpers around the robot's base, and a photodiode, located under the robot's base, used to follow tape on the floor. The researchers concluded that implementing artificial intelligence in robots is limited by how well the sensor system can determine the true nature of the environment.

Video Vision Robot Guidance

Research is being conducted at the University of Virginia[39,40] on guiding autonomous and semiautonomous vehicles using three-dimensional vision systems. Their work is specifically aimed at highway vehicles. The approach is to identify texture and changes in texture in the roadway scene using a priori information. The pathway is identified using edge detection techniques. Range detection and obstacle avoidance are addressed using stereo vision techniques. The navigation algorithms were processed on a PDP 11/44 minicomputer. The camera used to obtain images was a solid-state 100 by 100 pixel Reticon RS250. These researchers do not have a moving system at present.

ROBART II

ROBART II is an autonomous sentry robot.[15] ROBART II has seven ranging modules made by Texas Instruments for use with Polaroid ultrasonic transducers. Five of the transducers are configured in an array mounted on the robot's body and always face in the direction of travel. The two remaining transducers are mounted on the robot's head and rotate along with the head. The array of ultrasonic sensors increases the angular resolution of sensor information because of the overlapping ultrasonic beams. This makes obstacle avoidance easier. The robot also uses a temperature sensor that enables the robot to compensate for the dependency of the speed of sound on air temperature. The robot is also programmed to track an intruder when it is in the sentry mode.

Path Relaxation[28]

Path relaxation is part of the navigation systems of the Pluto and Neptune mobile robots at CMU. Path relaxation is performed in two steps. First, the global model is covered with a grid of eight connected points. The robot chooses a rough path along the nodes of the grid based on the cost of each node. The node cost is composed of costs for distance, for being near objects, and for being within or near an unmapped region. The optimal path is found using a A* search.[35] Second, the nodes are moved or "relaxed" in order to minimize the total cost. The relaxation step has the effect of turning jagged paths into straight paths wherever possible.

Spatial Representation System[41]

This world modeling system is intended for the Heathkit Hero-I robot or any other personal robot currently on the market (possibly Arctec Systems GEMINI, ComRo by Comro, Inc., or RB5X by RB Robot Company). The mobile robot is intended to have a low acuity ranging sensor (probably ultrasonic).

This guidance system represents the world as a flat, open plane with vertical walls and obstacles. The basic unit for representing the space is the Map. A Map contains linked regions. Since the robot has three degrees of freedom (two planar and one orientation), there are four types of regions: O-F, 1-F, 2-F, and 3-F. A j-F region is a region in which the robot can eliminate j degrees of freedom. For example, an O-F region has no obstacles or walls within the maximum range of the depth sensor. Navigating from one region to another is done using an algorithm that uses Voronoi diagrams of the polynomial regions. Because of the way the world is represented, this guidance system is limited to manmade indoor environments.

Visual Map Making

Brooks[42] from the Massachusetts Institute of Technology (MIT) Artificial Intelligence lab describes a map-making system for use on a mobile robot equipped with sonar sensors. His navigation algorithm explicitly represents uncertainties in the robot's postion. The key idea is to use a rubbery and stretchy relational map instead of trying to place observations in a two-dimensional absolute coordinate frame. Free space is represented as "freeways" which are elongated regions of collision-free pathways for the robot.

Multi-Goal Real Time Path Planning

Parodi[43] of FMC Corporation, Central Engineering Laboratories Artificial Intelligence Center, presented a global path planning subsystem for an autonomous land vehicle (ALV). Path planning is divided into three hierarchical levels: (1) action planning determines path specifications from orders to move from one location to another, (2) global planning has an expert compute a path description for local path planning according to the global map and path specifications, and (3) local path planning is performed by an expert (pilot) using sensor information. The world model consists of a square grid map in which each node contains altitude, terrain code, and a pointer to record information such as a landmark description. The navigation algorithm is based on computing the cost to travel from the ALV's present location to its goal by using a combination of dynamic programming and path relaxation.[28] The researchers used a computer simulation program to test the algorithms. Vehicle and terrain descriptions could be changed in the program. The results of tests so far show that the subsystems' computation time is too long. High speed implementation has been studied to eliminate this problem.

Intelligent Mobile Autonomous System (IMAS)

Ongoing research into an IMAS with an intermediate path planning subsystem (navigator) which operates in completely known, partially known, and completely unknown environments is being conducted.[44] A "cartographer," which performs map updating, passes information from the sensor to the navigator. The IMAS uses a hierarchical control structure. All motion planning is distributed between three levels of decisionmaking. These three levels are: (1) the planner which performs gross route planning on a large scale, (2) the navigator, which receives intermediate goals from the planner and does intermediate path planning, and (3) the pilot, which represents the lowest level of decisionmaking. The pilot executes real motion path planning for the navigator and is also responsible for obstacle avoidance. The world is composed of two-dimensional polygonal obstacles represented by a list of their vertices. The approach used by this navigation system uses a concept termed "sectors" and a heuristic A*-like search[35] which can deal with maps which may be known or partially unknown. These researchers feel that their current research gives them the opportunity to implement path planning procedures on an actual mobile device.

Natural Decomposition of Free Space

Kuan et al[45] have developed a navigation algorithm that decomposes free space into nonoverlapping geometric-shaped primitives suitable for path planning. Given a set of polygonal obstacles, concave obstacles are decomposed into connecting convex obstacles. Convex polygons make it easier to determine the minimum distance between obstacles. The relationships between obstacles are identified in order to locate "channels" and "passage regions." Channels are represented as shapes similar to cones and passage regions are convex polygons. Path planning is done by using an A* search algorithm to find the optimal path between two goals.

Summary of Guidance System Approaches

Several basic components are essential to any successful mobile robot guidance system. The way in which a robot models its environment greatly affects how it plans a path between obstacles from starting position to final destination. There are several levels of path planning. These include global planning, which means large scale path planning on a map of the world, usually taught to the robot in some sort of a learn mode. Local path planning is the next step. At this level, the robot determines its position on the world map and plans the best path to intermediate goals by examining sensor data. The robot also uses sensor data to update the world map. The lowest level of navigation is collision avoidance. The robot achieves this by the use of proximity sensors. Although the levels of path planning are essentially the same for different navigation algorithms, the approaches used for path planning are different.

Thorpe and Matthies[23] outline several approaches to path planning currently being used. In the first two approaches, Free Space[17,26,41] and Vertex Graph,[3] obstacles are modeled as polygons or circles, which is inappropriate for many real life situations (e.g., outdoor mobile robot guidance). Both methods break down free space into a graph of possible paths. The shortest path is then found by using some standard search technique such as an A* search.[35] In Free Space methods, the robot moves down the center of open corridors (e.g., on the Voronoi diagram of free space). This has drawbacks because in a large corridor, the robot may be traveling way out of its way. In Vertex Graph methods, the shortest path from starting position to goal intersects vertices of obstacles, so that the path tends to hit corners of obstacles. This can be improved by expanding the obstacles by some safety factor to account for the robot's size, but this can also block an otherwise open path. Another approach, which also chooses the shortest path, is the Regular Grid method.

The Regular Grid method consists of covering the world map with a grid of points, each connected with its four or eight neighbors to form a graph. Each node is either in free space or in an obstacle. The grid is then searched to find the shortest path along the nodes. All of the above methods suffer from the problem that the shortest path is not necessarily the best path. In addition, unmapped regions have to be closed off entirely.

The Potential Fields approach has been used in robot manipulator guidance systems. This method models obstacles as hills with sloping sides. The robot can move closer to obstacles with steeper slopes than obstacles with shallower slopes. The robot seeks to move through valleys between hills or through areas with a lower potential. One problem with this is that the robot may move into a dead end, in which case it must retrace its path back out and start again. Moreover, the path may turn out to be a long and winding road when a path over a small obstacle at first may lead to an easy path to the goal.

Path Relaxation[3,28,30] combines features from Potential Fields and Regular Grid methods. In this approach, a grid is laid over the world map as before and the shortest path is found using a search technique. Then the nodes are moved or "relaxed" closer to or farther from obstacles depending on a cost function based on the terrain where they are located. The success of all these path planning algorithms depends on a very accurate world map.

Another approach to path planning does not require a world map, but is subject to limitations. When a goal-seeking sensor[20] is employed by a mobile robot in a structured environment, such as a factory, it moves in the direction of beacons placed at goals. The beacons would probably be located at work stations. The only path planning required would be obstacle avoidance algorithms. This approach does not work if the beacons become obscured. This limits the robot to operating in a known environment. No matter what path planning approach is used, it is only as good as the information obtained from its sensors.

Presently, researchers have access to vision systems and laser range finders for short- to long-range sensing. They also have access to ultrasonic sensors for short-range and proximity sensing, and contact switches, magnetic, and infrared sensors for proximity sensing. Wheel encoders are very popular for estimating position through trajectory integration. Inertial guidance, goal-seeking, and global positioning systems are also being looked at in mobile robot research. By comparing what is available to what is desired, it is possible to make recommendations for continuing mobile robot research. The next chapter makes suggestions for applying current technology to mobilization construction robots.

4 APPLYING CURRENT SENSOR AND GUIDANCE TECHNOLOGY TO MOBILIZATION CONSTRUCTION ROBOTS

Introduction

This chapter is organized into three sections. The next two sections discuss indoor and outdoor guidance systems, respectively. These two sections are divided into five subsections: (1) task characteristics, (2) environment, (3) required guidance system functions, (4) needed sensors, and (5) needed guidance system software. The final section combines all of this information in order to make recommendations for applying current mobile robot technology to mobilization construction and identifies technology shortfalls in this area.

Indoor Guidance System

Task Characteristics

The General Purpose robot (see Chapter 2) would be required to perform connecting and finishing operations on the interior of an Army building under construction. Typical tasks envisioned for such a robot are nailing sheets of drywall or plywood, taping drywall, and painting. The task this type of robot performs would be limited by the end effector mounted on its arm. Each type of General Purpose robot could use the same generic guidance system for navigating around the interior of the building regardless of which type of end effector is mounted on it. Once the robot has reached its destination, it becomes a fixed robot. At this stage, the task becomes one of guiding the robot's arm and end effector, which current robotic manufacturing technology is able to do.

Environment

The General Purpose robot would operate in a series of rooms with wood frame walls and plywood floors. All the floors on the same story of a typical facility are on the same level with the exception of the entranceways and the shower area. This means that the robot would have to negotiate few changes in floor level. Depending on the stage of construction, the robot would be exposed to all types of weather. The robot basically must operate in a manmade environment with planar-faced walls. If the operation is performed before the drywall sheets are installed, the environment would consist of planar-faced walls covered with vertical 2 by 4 studs and exterior siding. Once the robot's surroundings and tasks are known, it is possible to determine what type of sensor and guidance system is needed.

Required Guidance System Functions

An indoor guidance system for this application will be required to perform the following functions after it is given instructions from its operator.

1. Guide the robot to a prescribed room.

2. Guide the robot to a prescribed area of the room.

3. Avoid collisions with obstacles.

4. Guide the robot around the room and stop it at desired positions.

5. Coordinate activities with workers and other robots.

When the robot is stopped at a desired position, a local sensing system must take over. It will guide the robot's arm and end effector to perform a specific construction task.

Needed Sensors

The sensors for indoor construction robots have to be able to detect walls, doorways, and obstacles inside a building under construction. Obstacles in a building would include scraps of lumber on the floor, small containers of supplies, large stored items, cables on the floor, as well as moving people and robots. There are several sensing strategies to choose from for this application.

1. Ultrasonic Transducers[13,14,15]

Ultrasonic transducers are quite able to provide the information required for guiding a mobile robot in an indoor mobilization construction environment. They are relatively inexpensive and can provide range data in real time. They also can be used as proximity sensors for collision avoidance and short range sensing.

2. Contact Switches[11,16,17]

Contact Switches placed around the base of the robot can also be used as proximity sensors. This simple type of tactile sensing can detect objects that the ultrasonic sensors might miss.

3. Wheel Encoders[11,16,17]

Wheel encoders placed on the drive shafts of the robot can be used as another source of information for position estimation. The type of surface (plywood floors) that the robot drives over would cause less wheel slippage than other more slippery surfaces.

4. Vision System[6,12]

Current vision systems are too slow and costly in terms of computer processing to be practical for guiding a robot through a building under construction. However, a vision system can be used to guide a robot arm and end effector, as is evidenced by many such systems used in manufacturing. For example, a vision system could be used to track a seam between sheets of drywall.

5. Goal-Seeking Sensors[20]

This sensing strategy would entail placing beacons at strategic locations, such as doorways. This could really enhance the guidance system, but it would be preferable if the robot could navigate inside the building without it.

To process the information gathered from the sensors, the mobile robot must have an intelligent world modeling and navigation system. World modeling and navigation using sensors could be accomplished with computer software implementation.

Needed Software

The first step in developing a practical navigation system is to model accurately the robot's surroundings. For a world map, the robot could be given the floorplan of the building--complete with the locations of rooms (i.e., absolute map) and relationships between rooms (i.e., relational map). The robot's world representation system would actually consist of two related maps. The absolute map would contain room location and distance information with respect to an absolute coordinate frame. The relational map would be a semantic network[46] with each room being a node. The links between nodes would show what other rooms that a particular room has access to. The rooms could be named ROOM1, ROOM2, etc. In addition, each room would have a local coordinate frame associated with it. The robot would use this frame to place objects in the room detected by sensors. Using this scheme to represent the knowledge of room locations and relationships, the robot can then use its knowledge base to plan actions.

The robot would have three levels of path planning--global, local, and obstacle avoidance. For global planning, the robot would examine its absolute and relational maps to plan a path to the desired room. Once the robot is in the desired room, it examines the local map of the room and updates obstacle information using sensor data. It can then plan paths for construction activities and obstacle avoidance using information received from sensors, workers, and other robots. Several different approaches to path planning were discussed in Chapter 3. For this application, a path planning approach that returns the shortest path to the goal would be better than one that tries to minimize the cost of moving through different kinds of terrain. This is because for this application the world is a plane with areas that are either open or occupied. No consideration has to be made for varying terrain or changing the elevation. For this reason, Vertex Graph,[3] Free Space,[17,26,41] or Regular Grid[28] methods can be used for path planning.

Outdoor Guidance System

Task Characteristics

The three types of outdoor mobilization construction robots required for mobilization construction are the Assembly, Material Handling, and Site Preparation Robots (See chapter 2). These robots will initally be conventional construction machinery equipped with autonomous guidance systems.

1. Assembly Robot

Typical tasks for the Assembly Robot include placing floor trusses, wall panels, and roof trusses on the building foundation. Another task would be positioning and nailing plywood sheathing on the exterior wall panels of the building. Performing these tasks on a building will require a reach of 6 to 7 m. To move large building components, this robot could resemble a building crane equipped with an autonomous guidance system.

2. Material Handling Robot

The Material Handling Robot will be required to transport building material (lumber, insulation, and shingles), and equipment from the warehouse to the construction site. Once at the building site, the robot must deposit the material at prescribed locations around the building so that the Assembly and General Purpose Robots can access it. This type of construction robot is envisioned as a vehicle equipped with an automatic loading and unloading system and a guidance system. Material handling inside the warehouse would be accomplished by a different type of robot.

3. Site Preparation Robot

This type of construction robot will be required to perform site preparation tasks (e.g., install buried utility systems) before the concrete slab is poured. For mobilization construction, utility systems include electrical, water, sewer, and communication lines.

Environment

The environment for these robots is essentially the exterior of a mobilization facility under construction. This means that the robot's surroundings will consist of rough terrain with no surface drainage control. The robot must be able to contend with unpredictable weather. The surroundings will include many obstacles, both stationary and moving. The robot must be able to avoid open ditches and muddy areas as well as avoid collisions with workers, piles of building material, construction machinery, and other robots.

Required Guidance System Functions

Although the three types of outdoor construction robots discussed above have different construction tasks to perform, they do require some of the same guidance system functions. Several functions performed by outdoor construction robots are similar to those of indoor construction robots, except the functions are carried out in a much less structured environment. This results in different requirements for sensor and guidance systems. Also, due to the unstructured and dynamic environment of construction, and outdoor construction in particular, it is impractical to totally replace human workers. For this reason, extra care has to be taken to ensure the safety of human workers.

1. Assembly Robot

- Guide the robot to prescribed positions around the building to perform material placing and connecting activities.

- Guide the robot to prescribed positions around the construction site to pick up building materials.

- Avoid collisions with obstacles.

- Coordinate activities with workers and other robots.

2. Material Handling Robot

- Guide the robot from warehouse to work site.

- Guide the robot to prescribed positions around the work site to deposit building materials.

- Avoid collisions with obstacles.

- Coordinate activities with workers and other robots.

3. Site Preparation Robot

- Guide the robot to prescribed areas around the work site.
- Guide the moving robot as it performs its site preparation task.
- Avoid collisions with obstacles.
- Coordinate activities with workers and other robots.

Each type of outdoor construction robot also requires a local sensing system for guiding its end effector. In the case of the Assembly and Material Handling Robots, a local sensing system will guide the end effector in many instances while the robot is not moving. In the case of the Site Preparation Robot, the local sensing system will have to guide the end effector while the robot is moving.

Needed Sensors

Since the environment of the outdoor construction robot is much more complex than the environment of the indoor construction robot, it will require a more sophisticated sensor system.

1. Ultrasonic Transducers[11,14,15]

In this type of environment with many irregular objects, it is difficult for an ultrasonic transducer to provide the accuracy needed for position estimation. Also, ultrasonic transducers do not have the range required for many outdoor ranging tasks. However, they can function quite well as proximity sensors for short range sensing and collision avoidance.

2. Contact Switches[11,16,19]

Contact switches around the perimeter of the robot are essential as a fail-safe method for avoiding collisions.

3. Wheel Encoders[11,16,17]

Wheel encoders can provide another source of information for position estimation.

4. Vision System[6,12]

A practical vision system is essential for guiding the robot and its arm in an outdoor construction environment. It can be used for three-dimensional sensing, object recognition, object orientation, and as a global positioning system using fixed markers.

5. Goal-Seeking Sensors[20]

Due to the complex environment, homing beacons placed at strategic locations on and around the building site would aid the robot in finding prescribed areas.

6. Infrared Sensors[9,11,19]

Infrared sensors can be used as proximity, motion, or goal-seeking sensors.

7. Laser Range Finder[14]

The outdoor construction robot will need to be able to determine the range of objects over much greater distances than the indoor robot. A laser range finder could provide range information for objects that are beyond the range of ultrasonic transducers.

8. Level Sensors[11]

Level sensors are needed to inform the robot if it is traveling up or down too steep a grade. This will help keep the robot from overturning.

9. Local Positioning System[11]

The development of a local LORAN type global positioning system would allow the robot to accurately determine its position on its world map.

Needed Software

Because of the complex nature of the outdoor construction environment, an idealized world map (two-dimensional, flat, and planar-faced obstacles) will not contain enough information for the outdoor construction robot to plan paths and navigate. Therefore, the robot needs a world map which is a three-dimensional representation of the environment. Brooks[42] is using a rubbery and stretchy relational map instead of trying to place observations in a two-dimensional absolute coordinating frame. Some type of combination of absolute and relational world maps, which are a three-dimensional representation of the environment, is needed. Also, the robot needs to dynamically model the world because of the rapidly changing surroundings. For global positioning, the robot can make use of fixed beacons, and it should be able to establish intermediate landmarks. As in the case of the indoor robot, the outdoor robot also needs three levels of path planning--global, local, and obstacle avoidance.

For outdoor construction applications, the robot needs a path planning approach that determines the best path to a goal. In this case, the shortest path is not necessarily the best path. Of all the path planning approaches available to mobile robots, path relaxation appears to be the best for this purpose. An additional feature which an outdoor construction robot needs, is the ability to communicate with workers and other construction robots. It can use this communication to correct path errors or to coordinate activities.

Recommendations

Indoor Guidance System

Guiding a robot in this type of environment (manmade, planar-faced objects, and flat) is similar to what many researchers are working on. The following work should be done to implement such a guidance system on a mobile robot. Researchers should concentrate on developing an interactive computer simulation program for an Arctec-GEMINI mobile robot which accurately models a building under construction, the GEMINI, and its sensor system. Navigation algorithms using different approaches to path planning can then be investigated for moving through the interior of the building. As deficiencies in the GEMINI's sensor system are discovered, they can be corrected concurrently with the refinement of the navigation algorithms. Once a workable sensor and guidance system is demonstrated on the GEMINI, research can be conducted on the development of a General Purpose Robot capable of supporting and controlling an arm and end effector for specific applications. There are, however, many deficiencies in sensor and guidance technology, requiring basic research, which will be discussed in the next chapter.

Outdoor Guidance System

The current state of the art in outdoor mobile robot sensor and guidance technology is still in the conceptual and experimental stage. Some success has been achieved in highly limited applications, such as following a road under highly idealized conditions. A world modeling system needs to be developed which can accurately represent the real world. By combining different types of sensors into multisensor systems, the robot can obtain enough information to guide itself in an outdoor environment, but with current technology, it is unable to process the information fast enough to provide a practical guidance system. Significant research into increasing information processing time especially for vision systems, must be done. Research is being done on parallel processing and special VLSI chips to more efficiently process sensor data. Path planning is limited by an inaccurate world model and insufficient sensor information processing times.

Guidance systems for outdoor mobile construction robots, such as those discussed above, are not feasible with current sensor and guidance technology. Not only is an accurate world model needed, but also an accurate model of the robot vehicle itself. Treating the robot as a point moving in the world is not appropriate for this application. Besides guiding the robot itself, significant work must be done to accurately control arms and end effectors which are required to move large and heavy objects. Information learned from guiding mobile robots in the more idealized indoor environment can provide insights into guiding robots in an outdoor environment. The goal now is to make outdoor construction machinery more efficient. Since it is impractical to totally replace human construction efforts, one should strive to increase their productivity. This can be accomplished by adding artificial intelligence to construction machinery. Although it is impossible with current technology to have a practical autonomously guided piece of outdoor construction machinery, it is possible to make the machine more intelligent by using sensor and guidance systems. This will increase productivity and reduce dependency on skilled labor at construction sites.

5 BASIC RESEARCH ISSUES

Introduction

Adapting robots to construction applications poses many interesting and challenging basic research issues that have not been explored simultaneously in both construction and robotics research. From the construction point of view, for example, new construction technology and management approaches may need to be developed to form a more uniform and structured construction environment so that mobile robots, with only limited intelligence, can still function well on construction sites. This calls for basic research efforts in construction engineering. On the other hand, from the robotics point of view, more intelligence must be added to the current production robots and basic research is needed in the areas of mobility and sensor and guidance systems. One of the goals in this assessment effort is to identify the basic research needs in sensor and guidance technology that will make robotic construction viable. Therefore, the emphasis of this chapter is on this particular aspect of construction robots, although other subjects, such as the mechanical and control aspects of mobile robots and the construction technology, are also crucial to the overall goal and require basic research.

Before recommending basic research needs in sensor and guidance technology for mobile construction robots, it is worthwhile to clarify the definition of basic research. Here, basic research means efforts that are essential to accomplishing the goals of robotic construction, but are neither robotic systems nor construction activities specifically. These efforts must unavoidablly be long-term, but they will result in significant contributions to robotic construction and to broader aspects of robot and construction technologies. They should address the fundamental and generic issues of the technology, and will certainly be much more involved. Identifying these basic research topics indicates the scope of the problem and proposes general suggestions on how to approach these problems. No details of these approaches are identified at this stage.

For the purpose of discussion, this chapter divides basic research issues for mobile construction robots into software and hardware aspects. It should be noted, however, that this division is somewhat artificial since there is no task in this area that is purely a software or a hardware problem.

Basic Research Issues in Software Aspects

Comprehensive World Model

--to develop a competent world model that contains not only geometric information such as construction site maps but background knowledge about the robot's construction tasks and environment.

An accurate and comprehensive world model forms the foundation of a successful navigation system for mobile robots. In modeling the world for mobile robots, previous efforts have been focused on establishing the map hierarchy (i.e., global and local) and employing a two-dimensional representation of the world.[9,17] This approach has successfully reduced the complexity of the world model, but has severely limited the operating environment of a mobile robot. Many applications, including outdoor construction, need a three-dimensional representation of the world. This will allow robots to locate themselves and other objects in their surroundings with respect to an absolute three-dimensional coordinate reference frame. This far more difficult problem has been the focus of several research efforts, but no practical solutions have yet resulted. Another important requirement of this map is that it must be a dynamic map that can be modified continuously. This is very important when robots are to be operated in unstructured environments. In this situation, a robot must be able to update the world map by using sensor information. This problem has also been addressed in several mobile robot research efforts, yet a fundamental understanding of how the world should be represented and updated is still needed. One difficulty of this task comes from the fact that current world maps make no provisions for tracking moving objects. This feature is essential if a robot works in an interactive environment such as a construction site.

In addition to an absolute world map that allows a mobile robot to determine its position and orientation with respect to a reference frame, a relational world map is also needed in a practical robot navigation system. A relational map could be constructed as a semantic network with each specific place being a node. The links between nodes indicate what other places are accessible from a particular place. For indoor manmade environments, each node could be a room; for outdoor open environments, each node could represent a particular area of interest. A more structured and complete world representation can be achieved by combining this relational map with an absolute map.

A map is not the only information that a mobile robot needs to accomplish its task successfully. Maps, even with the most complete version of dynamically updated absolute and relational information, contain nothing but geometric information of the world. To be able to navigate intelligently and accomplish tasks efficiently, information other than geometric is needed. Background knowledge that describes tasks, related information, and environmental implications is very important to construction robot operation and should be included in the world model. The background knowledge would include the types of activities to be performed in a specific area or room under certain situations. If, for example, a mobile robot is told that a room is just being painted, it would use the background knowledge to know that no nailing activities should be performed in that room at the present time. The artificial intelligence approach, knowledge-based expert systems in particular, could be a great help in this pursuit. Incorporating artificial intelligence and knowledge-based expert systems into the software of construction mobile robots is unavoidable. No existing basic research effort is aimed at this topic.

Realistic Robot Model

--to develop a more accurate and realistic model for mobile robots that will result in more efficient obstacle avoidance and more precise position estimation.

An accurate and comprehensive world model is only the first step in developing a successful guidance system. An accurate model of the mobile robot itself is also needed for operation and navigation in a construction environment. Several path planning systems discussed in this report represent the robot as a point and then expand the obstacles by some safety factor. This method has several inherent problems. One of these problems is that expanded obstacles can close off an otherwise open passageway. This results in very conservative obstacle avoidance paths. This type of system is fine for a cylindrical mobile robot, but difficulties are encountered if the robot is not symmetrical. Therefore, to navigate through an unstructured environment, such as a construction site, without collisions with foreign objects and other robots, a more accurate robot model is very important and is a challenging basic research topic.

As in path planning and collision avoidance, position estimation also requires an accurate model of the mobile robot. For a mobile robot to estimate its position, it must know its response to steering inputs at various speeds. For example, one of the ways to estimate a mobile robot's position is by the use of wheel encoders. Inaccuracies are caused by wheel slippage and moving over uneven terrain. A means to accurately record the total straight line distance travelled over rough terrain is needed. Wheel encoders only give the distance travelled over flat surfaces. By combining the information obtained from wheel encoders and level sensors, one could estimate straight line distances over uneven surfaces. Since the hardware (i.e., wheel encoders and level sensors) is available, this is mainly a software problem.

Hierarchical Sensor Control

--to develop a control hierarchy for sensory information and activities that occur in navigation and operation when performing construction tasks.

Mobile robots need a means to effectively handle multisensor systems. Manipulating a continuous stream of information from several different sensors simultaneously is very costly in terms of computer storage space and processing time. This problem should be attacked from both the hardware side and the software side. From the software point of view, one way of achieving this goal is to structure the expected activities so that a hierarchy can be established for the interactions of sensory information and operations of different sensors. To achieve a higher level of efficiency, this hierarchy will unavoidably be activity-dependent. Therefore, developing specific hierarchies for construction applications is another basic research need. In the case of navigation within construction sites, for instance, the hierarchy must be able to control the use of different sensors based on the level of guidance or operation being performed. It should have the ability to break down the overall goal (i.e., maneuver through a room or joint two trusses) into logical steps so that at each individual step it needs only to activate the fewest sensors and interact with this sensory information. During operation, the robot will consistantly monitor its activity to determine its current location on this hierarchy so that sensory activity can be focused and sensory interactions can be limited. The hierarchical decisionmaking approach that has been previously developed[4,7] could be a starting point in pursuing this research.

As an example, if a mobile robot is about to navigate through a construction site, a sensory strategy based on the "activity hierarchy" would be to first determine its heading (direction), then to locate beacons to calculate the distance from them and finally, to combine the direction and distance to estimate its current location and take proper movements. At each instance, the robot only needs to activate appropriate sensors (e.g., compass for direction and ultrasonics for distance) and focus its computing power on this particular type of sensory information. In this way, an effective guidance system can be implemented with limited computer resources locally available to the robot.

Dynamic Sensory Systems

--to develop more powerful sensory systems that are able to dynamically trace objects moving in three-dimensional space while the sensory devices themselves are travelling with the mobile robot.

In theory, the sensory systems for mobile construction robots should be able to perform sensing while the robot is travelling and should be able to follow the trajectory of a moving object within the construction site. In practice, however, this is not yet possible and requires major basic research efforts. Processing information gathered from sensory systems is too slow and unreliable based on the current available technology. Also, processing a moving scene is extremely difficult, except in limited applications such as moving in a manmade environment at very slow speeds. Visual guidance algorithms require the robot to stop and take a picture in order to use stero vision techniques to determine range information. It is desirable to be able to perform visual sensing while the robot is moving. It is also desirable for a robot's sensors to detect the movement of objects in its surrounding so that cooperation among multiple robots or between robots and construction personnel can be achieved. Software that can decrease processing time, reliably recognize objects, and provide accurate range information, is needed. Work in this area is required for processing both static and dynamic scenes. This is a combination software and hardware research issue.

Intelligent Local Positioning System

--to develop intelligent position estimation systems that will allow a mobile robot to find its own position based on insufficient or unreliable sensory (e.g., beacon) information within short range.

Research is needed to develop a local (short range) positioning system, which uses both active beacons and active receivers. On the software side, algorithms that allow position estimation based on insufficient and unreliable beacon information are needed. For example, if all beacons except for one were obstructed, a mobile robot should be able to estimate position based on the one beacon reading and some relevant background knowledge. This background knowledge will aid the robot to move intelligently to a different position where more beacon information may be received, or it might help the robot to navigate according to the estimated position temporarily until more reliable beacon information becomes available.

Collision Avoidance Systems

--to develop more reliable and effective collision avoidance systems that will enable mobile robots to move around confined space such as the interior of construction sites, and will guarantee the safety of construction personnel.

As previously mentioned, current collision avoidance approaches are not appropriate for construction mobile robots that must move around confined construction sites where many obstacles may be present. These obstacles may be construction components, raw materials, other construction robots, and personnel. The last case makes the collision avoidance problem a very serious one for robotic construction. Since unmanned construction is undoubtedly impractical even with future technology, any construction site will have workers perform hard-to-automate tasks in association with construction robots. The safety of these personnel will become a major concern if an effective and reliable collision avoidance system cannot be developed for construction robots. This safety issue raises another interesting basic research topic in collision avoidance.

Special Software for Construction Operations

--to develop special types of softwares that will control and coordinate construction robots to perform many specific construction tasks efficiently.

As indicated previously, adapting robots into construction may require some reorganization of the grouping of current construction activities. One advantage of grouping many different construction activities into several generic types of tasks is that for each generic task, special software for robot control, sensing, and end effector motion can be developed. For example, a special software may be designed that will help construction robots track and follow seams for caulking or sealing. Another special software may be developed to help construction robots carry out various joining tasks. This calls for basic research on the construction activities for software development.

Basic Research Issues in Hardware Aspects

Sensor Data Processing

--to develop dedicated and special purpose microprocessors to speed up the processing speed of sensory data.

The speed of processing information gathered from sensors (i.e., vision, proximity, and tactile) puts severe constraints on guidance systems. Processing speed can be increased through both software and hardware research and development. On the software side, as indicated earlier in this chapter, establishing a sensor hierarchy could help focus the processing power and thus increase the processing speed. On the hardware side, the application of VLSI technology to robotic sensing can greatly decrease processing time and is a very promising basic research area. Many special purpose VLSI microprocessors can be designed so that on line interactive processing of sensory data becomes a possibility. Some of the innovations discussed at a workshop on the application of VLSI for robotic sensing that are applicable to mobile robot sensors are: (1) a pixel correction chip, (2) an image sensor with 10^4 dynamic range, (3) VLSI enhanced architecture, (4) high-density serpentine memories, (5) an analog-signal preprocessor chip, and (6) inexpensive small proximity sensors.[48]

Special Computer Architecture

--to develop special computer architecture that is able to accommodate the software generated for mobile construction robots.

Work with computer architecture is needed to ensure that several different asynchronously controlled hardware devices such as sensors, navigation controllers, and manipulators are being used efficiently on a mobile robot. Additionally, the special software programs and hierarchies developed for the navigation and operation of construction robots need new computer architectures to be implemented. Some ongoing research in computer architecture may turn out to be very useful in this area. For example, work is in progress on parallel processing and using a hypercube architecture[28] approach. VLSI chips at the nodes of a tree or graph structure could be used to consistently and efficiently resolve multiple constraints such as those found in graph processing algorithms.[48] A powerful database architecture must also be developed to store world maps. These maps must be stored in a hierarchical fashion with distinctions made between local, global, absolute, relational, and functional aspects. A fast retrieval of information on any particular map is an essential feature of this computer architecture.

Communication and Monitoring

--to develop a method for communicating between the central computer and mobile robots within construction sites and design proper monitoring devices that will facilitate the central operation of the whole construction site.

A method for communicating between mobile robots and a central coordinating computer is essential. Communication between mobile robots must be through a nontethered connection, such as via a radio link. Mobile construction robots must be able to communicate with other robots or construction personnel either directly or through the central computer. The system should include communication hardware and software that determines which decisions should be made locally and which decisions should be made centrally. The central computer must also continuously monitor the system to make sure the desired orders are being carried out. Information about the overall construction site should be transmitted to this central monitoring device and displayed so construction system performance can be monitored. In addition, the central monitoring system should be informed when any construction robot is not functioning properly and should be able to detect malfunctions in the overall system. Therefore, basic research is needed to develop communication and monitoring hardware for a central monitoring room where humans and the central computer can interact efficiently.

Sensor Hardware for Construction Robots

--to develop and integrate more reliable and accurate sensors that are specifically suited for robotic construction.

The unstructured environment at construction sites generates very demanding requirements on sensory hardware. To be able to navigate mobile robots through construction sites and accomplish their expected functions, more reliable sensors must be developed and different sensors need to be integrated. Most sensors developed for indoor production applications are not satisfactory for construction activities. For example, the TV cameras currently used in computer vision are designed for eye viewing and vision tasks under controlled artificial applications. The disadvantages of TV cameras include nonuniform resolution (the best gain and resolution is at the center of the picture), poor linearity, camera tube lag, deflection of the electron beam by external forces, and fragility of video tube cameras. This indicates that much basic research effort is still needed to produce better sensor hardware before construction robots become a reality. The ROTOZOOM camera, for example, has started to address some of these issues.[7]

Sensor hardware is also needed for local positioning systems. Currently, many global positioning systems are used with great success for plane and ship navigation over wide-open space. These systems will not, however, be suitable for navigating mobile robots through construction sites where sensing is done at short range within confined space. Therefore, a powerful and reliable beacon system that will operate at the local or short range is needed. This will require the development of both active beacons as well as active receivers. Systems which use passive beacons, such as light-reflecting targets, are very unreliable in construction environments. Research to develop a short-range radar system could also answer some of the needs for navigating on an outdoor construction site. For example, RCA is working on short-range radar systems for a variety of applications.[13]

Conclusion

This report addressed several basic research issues in sensor and guidance technologies for mobile construction robots. For the convenience of discussion, these research issues were divided into software and hardware aspects. However, almost every issue calls for significant research efforts in both aspects. They are, in fact, not separable and should be considered as different views of the same problem.

Robotic construction needs technologies from both robotics and construction. Currently, each individual technology is still under development and requires many basic research efforts. Combining these two technologies to develop construction robots generates many basic research opportunities and also creates even more challenging research needs in these two contributing areas. This chapter is an attempt to identify these needs. It should, however, be noted that this chapter focuses only on the sensor and guidance system aspects of construction robots. Many other important topics, such as mechanics and control of mobile robots' manipulators, also call for significant basic research efforts and should be identified. Basic research for mobile construction robots will undoubtedly make major contributions to both robotics and construction engineering and will eventually make this new technology a reality.

Conversion Factors

1 m	=	3.28 ft
1 km	=	0.62137 mi
1 cm	=	0.394 in.

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APPENDIX:

SENSOR MANUFACTURERS (1983 List)

Assembly Machines, Inc.
4238 West 12th Street
Post Office Box 8326
Erie, PA 16505

Automation Industries, Inc. (Sperry Company)
Danbury, CT 06810

Automation Systems, Inc.
1106 Federal Road
Brookfield, CT 06804

Automatix, Inc.
217 Middlesex Turnpike
Burlington, MA 01803

Banner Engineering Corporation
9714 Tenth Avenue North
Minneapolis, MN 55441

Bendix Corporation
Automation and Measurement Division
721 Springfield Street
Dayton, OH 45401

Control Engineering, Inc.
1686 Riverdale Street
West Springfield, MA 01089

Delavan Electronics, Inc.
14605 North 73rd Street
Scottsdale, AZ 85260

Eaton Corporation
Cutler-Hammer Products
4201 North 27th Street
Milwaukee, WI 53216

EG&G Reticon
345 Potrero Avenue
Sunnyvale, CA 94086

Electromatic Components, Ltd.
742 West Aigonquin Road
Arlington Heights, IL 60005

Electronics Corporation of America
1 Memorial Drive
Cambridge, MA 02142

Fairchild CCD Imaging
4001 Miranda Avenue
Palo Alto, CA 94304

General Electric Company
Optoelectronic Systems Operation
3-201 Electronics Park
Syracuse, NY 13221

Gould, Inc.
103 Broadway
Bedford, OH 44146

GTE Laboratories
40 Sylvan Road
Waltham, MA 02254

Hamamatus Systems, Inc.
332 Second Avenue
Waltham, MA 02254

Heath Company
Benton Harbor, MI 49022

Hewlett-Packard Company
Optoelectronic Division
640 Page Mill Road
Palo Alto, CA 94304

Hewlett-Packard Company
1501 Page Mill Road
Palo Alto, CA 94304
(interferometer)

Hewlett-Packard Company
Post Office Box 301C
Loveland, CO 80537

Hitec Corporation
Nardone Industrial Park
Westford, MA 01886

Honeywell, Inc.
Photographic Products Division
5501 South Broadway
Littleton, CO 80120

Honeywell, Inc.
Solid State Electronics Center
10701 Lyndale Avenue South
Minneapolis, MN 55240

Hyde Park Electronics, Inc.
4547 Gateway Circle
Dayton, OH 45440

Integrated Photomatrix, Inc.
1101 Bristol Road
Mountainside, NJ 07092

Ivo Industries, Inc.
1109 Green Grove Road
Post Office Box 636
Neptune, NJ 07753

Kaman Sciences Corporation
1500 Garden of the Gods Road
Colorado Springs, CO 80933

Machine Intelligence Corporation
Palo Alto, CA 94304

Mark-Tech Laser, Inc.
2211D Fortune Drive
San Jose, CA 95131

Mechanical Technology, Inc.
968 Albany Shaker Road
Latham, NY 12110

Microswitch
A Division of Honeywell
11 West Spring Street
Freeport, IL 61032

Milltronics
2409 Avenue J
Arlington, TX 76011

National Sonics
250 Marcus Boulevard
Hauppage, NY 11787

Object Recognition Systems, Inc.
521 Fifth Avenue
New York, NY 10017

Octek, Inc.
7 Corporate Place
Burlington, MA 01803

Ohmart Corporation
4241 Allendorf Drive
Cincinnati, OH 45209

Omron Electronics, Inc.
Control Components Division
650 Woodfield
Schaumburg, IL 60195

Pickering and Company, Inc.
Measurement and Controls Division
101 Sunnyside Boulevard
Plainview, NY 11803

Polaroid Corporation
549 Technology Square
Cambridge, MA 02139

Rank Precision Industries, Inc.
411 East Jarvis Avenue
Des Plaines, IL 60018

RCA
David Sarnoff Research Center
Microwave Technology Center
Princeton, NJ 08540

Sagem
102 Boulevard Jean Jaures
95101
Argenteuil
France

Schaevitz Engineering
US Route 130 and Union Avenue
Pennsauken, NJ 08110

Selective Electronics, Inc.
Post Office Box 250
Valdese, NC 28690

Sira Institute
Optical Systems Division
South Hill Chislehurst
Kent BR 7 5EH
England

Solid Photography, Inc.
536 Broadhollow Road
Melville, NY 11747

Techmet Company
6060 Executive Boulevard
Dayton, OH 45424

Teletrac, Inc.
360 South Fairview
Goleta, CA 93117

Temposonics
131 East Ames Court
Plainview, NY 11803

Unimax Switch Corporation
Post Office Box 152
Ives Road
Wallingford, CT 06492

United Detector Technology
3939 Landmark Street
Culver City, CA 90230

Veeder-Root
Digital Systems Division
Hartford, CT 06102

Xolox Corporation
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